Journal of Forestry Research (2014) 25(2): 407–413
DOI 10.1007/s11676-014-0468-8

SHORT COMMUNICATION

A preliminary evaluation of throughfall sampling techniques in a mature coniferous forest

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Received: 2013-12-20; Accepted: 2014-02-12
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Abstract: Rainfall, throughfall and stemflow were measured and canopy interception loss was derived for 14 rainfall events from June 22 to August 30, 2008 within a mature declining hybrid white spruce (*Picea glauca* (Moench) Voss × *P. engelmannii* Parry ex Engelm.) - subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) - lodgepole pine (*Pinus contorta* var. *latifolia* Dougl. ex Loud.) stand in south-central British Columbia, Canada. Stemflow was negligible during the study period, while, respectively, throughfall and canopy interception loss accounted for approximately 59.4% and 40.6% of the 50.1 mm of cumulative rainfall. Throughfall variability was assessed with three approaches involving roving and stationary wedge-type gauges, and stationary trough gauges. Throughfall exhibited large spatial variability with the coefficient of variability of study period throughfall sampled using 16 stationary trough gauges being 30.3%, while it was 38.0% and 28.7% for 32 stationary and 32 roving wedge gauges, respectively. Our analysis suggests that a roving gauge method is better than a stationary approach since the errors associated with event mean throughfalls are summed quadratically and a greater portion of the canopy area is sampled. Trough gauges were more efficient than wedge gauges; however, this efficiency was less than expected given their much larger sampling areas, suggesting that spatial autocorrelation lengths of throughfall may be longer than the trough systems. The spatial distribution of throughfall showed a high degree of temporal persistence throughout the study suggesting the existence of stable "wet" and "dry" inputs to the floors of these coniferous forests.

Keywords: throughfall, canopy interception loss, stemflow, spatial variability, temporal persistence

Project funding: This research was funded by a British Columbia Forest Investment Account, Forest Science Program (Project # Y091045) grant and a National Science and Engineering Research Council (NSERC) Discovery Grant awarded to DC-M.

The online version is available at http://www.springerlink.com

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Corresponding editor: Yu Lei

Introduction

Canopy interception loss (I_c), the interception, storage and subsequent evaporation of rainfall (P_g) from forest canopies, has been shown to account for a sizable portion of the growing-season P_g input to forests in British Columbia, Canada. Spittlehouse (1998) found that from March 1995 to February 1996 I_c accounted for 30% of 3,316 mm of P_g that fell on a mature western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forest located along the west coast of British Columbia and 24% of 454 mm of P_g from May to October 1997 at a mature lodgepole pine (*Pinus contorta* var. *latifolia* Dougl. ex Loud.) with hybrid white spruce (*Picea glauca* (Moench) Voss × *P. engelmannii* Parry ex Engelm.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) stand in the south-central interior of the province.

Canopy interception loss is most commonly derived indirectly by taking the difference between measured incident P_g and understorey rainfall (Carlyle-Moses and Gash 2011). Understorey rainfall may either pass directly through canopy gaps or drip from the canopy, termed throughfall (*TF*), or it may reach the forest floor by flowing down the boles of trees in the form of stemflow (*SF*). Thus, I_c is typically found as:

$$I_c = P_g - (TF + SF) \quad (1)$$

In British Columbia *SF* is a minor component of the canopy water balance of many mature conifer forests accounting for approximately 1% or less of season-long P_g (Beaudry and Sager 1995; Spittlehouse 1998). Thus, the accuracy of I_c estimates in these mature stands is, for the most part, dependent on the accu-

racy of P_g and *TF* estimates. Although P_g estimates may be hampered by gauge catch error (Sevruk 1982), obtaining accurate *TF* estimates is complicated by the spatial heterogeneity associated with this component of understory rainfall (Price et al. 1997; Price and Carlyle-Moses 2003; Shachnovich et al. 2008).

One method of reducing the error associated with mean *TF* estimates is to use a large sample size, that is to use a large number of *TF* gauges (Helvey and Patric 1965; Kimmins 1973). Errors associated with mean *TF* catch spanning more than one P_g event will be smaller for sampling designs that require gauges to be moved after a certain time period has passed or P_g depth has been reached, hereafter referred to as the *roving gauge method*, compared to *TF* gauges kept in fixed locations throughout the study period, hereafter referred to as the *stationary gauge method* (Lloyd and Marques 1988). If a sufficiently large number of gauges are used and storms sampled, differences between the absolute mean *TF* estimates obtained using the stationary gauge approach and those derived using the roving gauge method will be negligible (Holwerda et al. 2006; Ziegler et al. 2009). However, the error associated with the mean *TF* estimate will differ (Holwerda et al. 2006). Biotic factors that may control the relative amount of *TF* that reaches the ground, such as foliage and branch cover (Staelens et al. 2006) or the proximity of tree boles (Johnson 1990), may result in non-random patterns of *TF* input that may be temporally persistent across an array of storms (Keim et al. 2005; Staelens et al. 2006; Zimmermann et al. 2007). Thus, spatiotemporal autocorrelation cannot be ignored when stationary gauges are used; however, the use of roving gauges removes this bias allowing the errors associated with an individual event or sub-period mean *TF* estimates to be summed quadratically since they may be assumed to be spatially independent (Burrough 1986). Using the roving gauge approach also allows for a greater proportion of the canopy to be sampled over the study period compared to using stationary gauges (Lloyd and Marques 1988).

An alternative to using a large number of fixed or roving gauges, which are usually cylindrical or wedge shaped gauges having catch areas that are typically <0.07 m^2 each (Keim et al. 2005; Staelens et al. 2006; Carlyle-Moses et al. 2010), is to use long trough gauges (Cantú Silva and Okumura 1996; Lankreijer et al. 1999; Lane et al. 2004; Cuartas et al. 2007). Because of their length and typically large catch areas compared to cylindrical or wedge gauges, trough gauges are thought to integrate the spatial heterogeneity of *TF* catch and, as a result, fewer trough gauges are required to achieve the same degree of accuracy associated with the mean *TF* estimate (Ziegler et al. 2009). Few studies, however, have concurrently evaluated the impact of *TF* gauge-type and stationary versus roving sampling methodologies on the accuracy of *TF* estimates in the same stand (Ziegler et al. 2009), and no known studies have been conducted in coniferous forests.

The objective of this research, in a mature declining coniferous forest of south-central British Columbia, was to report on a preliminary evaluation of *TF* sampling methods so that the most appropriate approach can be used in future studies in this forest and similar stands. In addition, we derived preliminary results regarding the quantitative importance of *TF*, *SF*, and I_c at the P_g event and season-long time steps for the study forest and we evaluated the temporal persistence of *TF* in this stand. We discuss here the impact of any identified temporal persistence of *TF* on the proper sampling of this water input.

Materials and methods

Site description

Measurement of incident P_g, *TF* and *SF* were made during the summer of 2008 (June 22 to August 30) at the Mayson Lake Hydrological Processes Study Area located approximately 60 km NNW of Kamloops, British Columbia on the Thompson-Bonaparte Plateau at 51°13′ N, 120°24′ W. The site, located at an elevation of approximately 1,260 m asl., is classified as being in the Dfc category of the Köppen climate classification system, a category described as subarctic with cool summers and cold winters (Ross 2013). Mean annual precipitation in the area is 559 mm with rainfall dominating during the growing season and snow dominating during the dormant season, while the mean annual temperature is 2.7°C with mean monthly temperatures ranging from -7.2–14.2 °C (Winkler 2010).

The stand was a mature declining hybrid white spruce (*Picea glauca* (Moench) Voss × *P. engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and lodgepole pine (*Pinus contorta* var. *latifolia* Dougl. ex Loud.) forest approximately 125 years-old. During the summer of 2008, most of the pines within the stand were at the late red attack stage of a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestation. Little needle fall occurred prior to or during the study period. A detailed stand survey conducted by Winler et al. (2014) showed when all trees (≥1 m height) were considered, the stand had a tree density of 3,631 trees·ha^{-1} and an average tree height of 9.9 m, while dominant/co-dominant tree density was 756 trees·ha^{-1} with an average height of 23.4 m. The basal area of the entire stand was 50.1 $m^2 \cdot ha^{-1}$ (mean diameter at breast height (DBH) of 11.2 cm), while the basal area of dominant and co-dominant trees was 34.5 $m^2 \cdot ha^{-1}$ (mean DBH of 24.1 cm). Canopy cover of the entire stand, measured with a moose-horn densiometer (Bunnel and Vales 1989) at each of 32 points in the stand, was about 58%. The understorey was comprised of a clumped spacing of fir saplings, while the forest floor was covered by an extensive bryophyte carpet comprised largely of red stem moss (*Pleurozium schreberi* sp.). Bunchberry (*Cornus Canadensis* L.) and falsebox (*Pachistima myrsinites* (Pursh) Raf.) were the dominant plant species found on the forest floor overlying the moss carpet.

Rainfall, throughfall and stemflow measurements

Rainfall was measured using a manually-read wedge-type rain gauge (Tru-Chek®, Albert Lea, MN, USA) located within a forest clearing 280 m SSE of the geographic centre of the forest study plot. The wedge gauge was situated so that the gauge opening

(36 cm^2) was 1 m above the ground with no obstructions extending above a 45° field-of-view centered on the gauge (as recommended by Brakensiek et al. 1979). Rainfall was measured on an event basis with an event defined as a P_g input ≥0.4 mm that occurred during a time period bounded by ≥8 h in which no measurable P_g fell. The 8-h dry periods bounding an event were chosen because observations in the field suggested that this was the maximum time required for the canopy to dry once saturated.

Throughfall was measured by wedge gauges of the type to measure P_g and trough gauges that emptied into manually-read cylindrical polyethylene gauges. Troughs were fabricated of galvanized sheet metal and were 240.1 cm (long) × 10.5 cm (wide), while the cylindrical gauge in which the trough emptied into had a diameter of 29.0 cm and a capacity of 17 L. Trough gauges were supported by two brace supports situated 30 cm from either end of the trough. The support near the end of the trough furthest from the cylindrical collection gauge was raised higher than the other support, so that the trough was angled 10° towards the collection gauge. Each trough + collection gauge had a total catch area of 3,027 cm^2, 84 times greater than that of the wedge-type gauge.

Thirty-two stationary wedge gauges, 32 roving wedge gauges, and 16 stationary trough gauges were used in our study. The study plot consisted of a grid comprised of four transects spaced at 8 m and along each of the four transects were 8 markers, again spaced at 8 m, giving a total of 32 evenly spaced markers. One stationary and one roving wedge gauge were situated along a randomly generated azimuth line at a randomly generated distance ranging from 0–400 cm from each marker. The fixed wedge gauges remained in place throughout the study, while roving gauges were moved to new randomly generated points around each marker after at least 15 mm of P_g had fallen. The locations of the stationary trough gauges were selected by first randomly selecting 16 of 32 marker locations, and then randomly selecting the point in which the cylindrical collection gauge would be located in the same manner that wedge gauges were placed. Finally a random azimuth was generated to determine the direction the trough would extend from the cylindrical collection gauge.

Stemflow was measured from nine randomly selected trees within the study plot comprising five pine, two fir, and two spruce trees. The diameter at breast height (DBH) and tree heights were considered typical of the dominant/co-dominant trees in the stand. Corrugated plastic tubing with a diameter of 3.2 cm was cut lengthwise to form a collar around each of the sampled trees. Each collar was spiralled around the tree bole and affixed to the tree using nails, while caulking sealed the inside lip of the halved tubing to the tree bole. Uncut tubing joined each collar to a 15 L collection vessel which was measured on a P_g event basis. Interception loss was derived using Eq. 1 from measured P_g, TF, and SF.

Statistical analysis

All descriptive statistics and regression analyses were completed using IBM SPSS 20 (IBM Corporation, Armonk, New York, USA). The number of TF gauges required to meet pre-determined statistical objectives was estimated using the following equation (Kimmins 1973):

$$n' = \frac{t^2 \times CV^2}{CI^2} \tag{2}$$

where, n' is the estimated number of collectors required, t is the Student's t-value (assumed to be approximately 2.0, Kimmins 1973), CV is the coefficient of variation expressed as a percentage, and CI is the confidence interval expressed as a percentage of mean TF.

The temporal persistence of TF was evaluated using the methodology of Keim et al. (2005). Throughfall was quantified by using standardized TF for each of the stationary TF gauge sample points using the following equation (Keim et al. 2005):

$$TFS_i = \frac{TF_i - TF_{mean}}{SD} \tag{3}$$

where, TFS_i and TF_i are the standardized and measured TF values at a point, respectively, while TF_{mean} and SD are the mean and standard deviation of TF for the storm over all gauges, respectively.

Standardized TF values are thus corrected to zero mean and unit variance. The temporal persistence of throughfall was evaluated using both a time stability plot (Keim et al. 2005) and by determining if mean TFS_i values at a point across all storms were significantly different from zero (p <0.05).

Results

Canopy water balance

During the period of late June to the end of August 2008 a total of 14 events were measured with a cumulative depth of 50.1 mm. Average event P_g depth was 3.6 mm and ranged from 0.4 to 8.5 mm. Of the 50.1 mm of P_g <0.1 mm (<0.1 %) was partitioned into SF. Stemflow was only generated during the largest P_g event of the study, 8.5 mm, and then only from six of nine sampled trees (SF volumes ranged from 6.4 × 10^{-2} to 1.36 × 10^{-1} L). Stemflow was not produced from the two firs or the smallest pine sampled.

Cumulative TF varied from 26.1 mm (standard deviation, SD =7.9 mm) using 16 stationary troughs to 32.4 mm (SD =12.3 mm) using the stationary wedge gauges. No significant differences (p ≤0.05) were found between the mean cumulative TF depth estimates using the three sampling techniques or between the slopes or intercepts associated with the relationships of event TF depth (mm) versus P_g depth (mm) for the three approaches. Thus, data from all gauges were pooled, with each gauge weighted equally, providing an estimate of cumulative TF of 29.8 mm, or 59.4 % of P_g. The relationship between pooled TF and P_g at the individual rainfall event scale is shown in Fig. 1

with the equation of the linear regression being:

$$TF = 0.735P_g - 0.528 \quad r^2 = 0.91 \tag{4}$$

From Eq.1, I_c during the study period was derived as 20.3 mm, or 40.6 % of P_g. The relationship between I_c depth (mm) and P_g depth (mm) is given by the following equation:

$$I_C = 0.260P_g + 0.542\,,\ r^2 = 0.57 \tag{5}$$

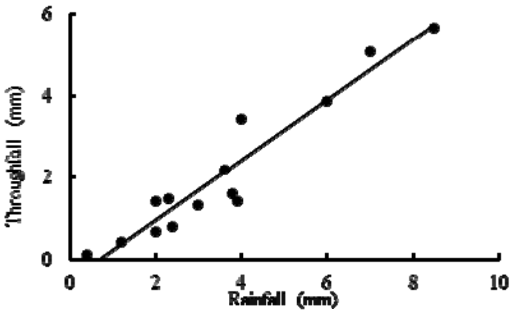

Fig. 1: Throughfall (all gauges combined) in the study stand as a function of rainfall depth

The canopy water balance components, expressed as both a depth and a percentage of P_g, for each event are listed in Table 1.

Table 1: Canopy water balance values on a rainfall event basis during the study period

Event date (2008)	P_g	TF/mm (%)	SF/mm (%)	I_c/mm (%)
21/06	3.6	2.2 (60.6)	0.0 (0.0)	1.4 (39.4)
30/06	3.9	1.4 (35.9)	0.0 (0.0)	2.5 (64.1)
03/07	3.8	1.6 (41.6)	0.0 (0.0)	2.2 (58.4)
10/07	8.5	5.8 (67.8)	0.005 (0.06)	2.7 (32.2)
18/07	0.4	0.1 (25.0)	0.0 (0.0)	0.3 (75.0)
27/07	4.0	3.5 (86.5)	0.0 (0.0)	0.5 (13.5)
29/07	3.0	1.4 (45.3)	0.0 (0.0)	1.6 (54.7)
01/08	1.2	0.4 (36.7)	0.0 (0.0)	0.8 (63.3)
09/08	2.4	0.8 (31.7)	0.0 (0.0)	1.6 (68.3)
18/08	6.0	3.9 (65.7)	0.0 (0.0)	2.1 (34.3)
20/08	2.3	1.5 (66.1)	0.0 (0.0)	0.8 (33.9)
25/08	2.0	0.7 (34.0)	0.0 (0.0)	1.3 (66.0)
28/08	7.0	5.2 (73.7)	0.0 (0.0)	1.8 (26.3)
29/08	2.0	1.4 (71.0)	0.0 (0.0)	0.6 (29.0)
Total	50.1	29.8 (59.4)	0.005 (0.01)	20.3 (40.6)

Throughfall depth and spatial variability as a function of sampling technique

The CV of study period TF sampled using 16 stationary trough gauges was 30.3%, while it was 38.0% and 28.7% for 32 stationary and 32 roving wedge gauges, respectively. Roving gauges were relocated a total of three times during the study period. If, however, roving wedge gauges were relocated after each event the CV of cumulative TF associated with this approach would have been even lower. Assuming that the variability in event TF catch by 32 wedge gauges would have been similar regardless of their positioning, the roving gauge technique, with its associated quadratically summed error, would have resulted in a cumulative CV of 20.4%, if gauges were relocated after each event. Event CV values using both the wedge and trough gauges decreased asymptotically until TF depths of 3.5 mm were reached (Fig. 2). The CV of TF for individual events with TF depths ≥ 3.5 mm (P_g ≥4.0 mm) averaged 49.5% for the wedge gauges and was significantly larger (p =0.011) than the average of 31.9% for the trough gauges. For events in which TF averaged <3.5 mm the CV of wedge gauge TF, averaging 74.7%, was significantly larger (p =0.0002) than that of the trough gauges with average of 52.1%.

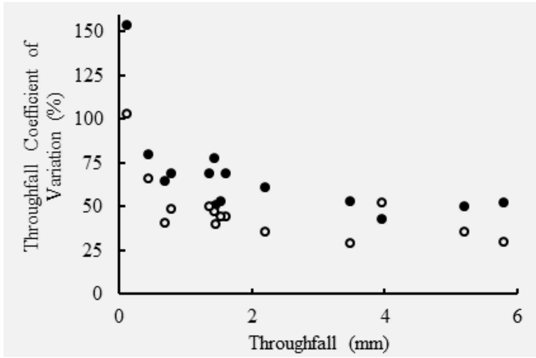

Fig. 2: Throughfall coefficient of variation using 64 wedge gauges (●) and 16 trough gauges (○)

Individual wedge gauges often recorded TF values that exceeded the incident P_g depth. In one case a wedge gauge captured 7.5 mm of TF associated with an incident P_g of 4.0 mm (188 % of P_g). Throughfall in at least one wedge gauge exceeded incident P_g depth during 12 of the 14 events. Zero TF was recorded in at least one wedge gauge during all events with the exception of the two largest events, 7.0 and 8.5 mm, which had minimum TF catches of 0.2 and 0.1 mm, respectively. The occurrence of extreme TF catches by trough gauges was lower than that associated with wedge gauges. Throughfall exceeded P_g in at least one trough gauge for 5 of 14 events, while no TF was recorded by at least one trough gauge only during three events.

The standard errors of the estimates of mean cumulative study period TF at the 95% confidence level were ±14.8%, 13.2%, and 9.9% using the trough, stationary wedge and roving wedge gauge approaches, respectively. With Eq. 2, the number of gauges that would have been required to estimate mean cumulative TF to within ±10% at the 95% confidence level was 36 stationary troughs, 56 stationary wedge gauges, and 32 roving wedge gauges. Assuming that the variability in TF catch at the event scale by 32 gauges would have been the same regardless of their random positioning, it is estimated that 16 wedge gauges would have been required to estimate mean cumulative TF to within ±10% at the 95 % confidence level if gauges were relocated after every P_g event. If trough gauges were relocated after each event,

according to Eq. 2, approximately six of these gauges would have been required to achieve the same degree of accuracy, suggesting that trough gauges are approximately 2.7 times more efficient than wedge gauges at the season-long time scale within the study stand.

At the individual P_g event scale the number of wedge gauges required to estimate mean *TF* to within ±10% at the 95% confidence level averaged 579, 160, and 94 for *TF* averaging <0.5, 0.5–3.5, and ≥3.5 mm, respectively. The number of trough gauges required to obtain the same level of accuracy for the three aforementioned *TF* ranges were 287, 75 and 40, respectively. Comparing the efficiency of trough gauges to wedge gauges, at the individual event scale one trough gauge was equivalent to using, on average, 2.2 wedge gauges (ranged from 1.4–3.0).

Temporal persistence of throughfall

Throughfall caught by stationary wedge gauges exhibited strong temporal persistence throughout the study period (Fig. 3). Fourteen and 11 of the 32 stationary wedge gauges (44% and 34%) had mean TFS_i values throughout the study period that were significantly lower and higher (p <0.05) than zero, respectively.

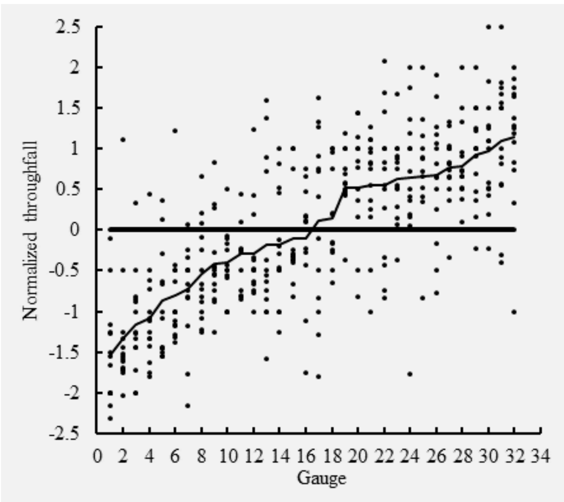

Fig. 3: Temporal stability of normalized throughfall for 32 stationary wedge gauges

Discussion and conclusions

Stemflow can be negligible in the study stand and may be excluded with little error in the I_c estimates derived using Eq. 1. Stemflow being completely absent from the fir trees was, in addition to the P_g depths during this study being relatively small, probably a result of the relatively dense canopy of this species which slopes down and away from the tree bole. Rainfall intercepted by such a canopy would either be stored within that canopy and subsequently evaporated, or would flow towards the periphery of the canopy resulting in increased *TF* inputs to the forest floor at the canopy edge (Price et al. 1997; Zhan et al. 2007). The absence of *SF* from the smaller pine was probably a consequence of a rain shadow created by larger neighbouring trees resulting in a lower effective P_g depth received by the small pine crown, a depth that was lower than the threshold required to produce *SF* (Levia and Frost 2003).

Canopy interception loss was estimated to be 41% of the cumulative P_g input during the study period. Although this value agrees well with the findings of certain studies conducted in other coniferous forests (Gash et al. 1980; Anderson and Pyatt 1986), comparing the I_c efficiency of forests based solely on I_c percentages might not be valid. The magnitude and frequency of P_g depths greatly influence the percentage of P_g partitioned into I_c (Gash 1979; Spittlehouse 1998; Carlyle-Moses and Gash 2011). In our study, only 50.1 mm of P_g fell over 14 events (average depth = 3.6 mm), while the following year, 2009, during the same time span covered in 2008, 85.4 mm fell over 16 events (average depth =5.3 mm), with one event totalling 41.5 mm. With Eq. 5, 30.9 mm of the 85.4 mm of the 2009 P_g record, or 36.2 %, would have been partitioned into I_c, representing a reduction in the I_c efficiency of the forest of 10% compared to the same period in 2008. These results suggest that the I_c efficiency of these spruce-fir-pine stands of the interior of British Columbia is due not only to stand characteristics but also due to the rainfall regime of the area which is comprised of a number of relatively small P_g depths. The fraction of P_g partitioned into I_c is thus highly sensitive to storm frequency and magnitude from one year to the next.

Throughfall was highly variable across the floor of the study stand. Even during the largest P_g event of the study the *CV* of *TF* catch using long trough gauges averaged 31.9%. As shown in Fig. 2, the variability of *TF* remained quasi-constant for *TF* ≥3.5 mm suggesting that this variability might not decrease under larger P_g event scenarios (Price et al. 1997; Carlyle-Moses et al. 2004). Throughfall variability might remain quasi-constant with *TF* depth for relatively large events because of the canopy either reaching or approaching saturation and the establishment of quasi-permanent canopy drip zones, where *TF* is concentrated, and canopy shelter zones, where intercepted P_g is either stored and evaporated or is diverted to other parts of the canopy or to the tree bole (Carlyle-Moses et al. 2004).

Intuitively, *TF* variability for relatively small events should be greater than that associated with relatively large events as a consequence of different areas of the canopy saturating and contributing to drainage at differing P_g input depths. While exposed portions of the canopy, especially foliage, wet first and potentially contribute to *TF* early during the wetting-up of the canopy phase, more sheltered portions of the canopy, as well as the woody component of the canopy, which typically has a greater storage capacity than foliage (Herwitz 1985), require greater P_g inputs to satisfy the threshold storage needed to initiate drainage in the form of *TF* (Calder 1986; Klaassen et al. 1998). For the smallest of events, we speculate that *TF* will only be in the form of free throughfall, that is P_g that passes directly through gaps in the canopy to the forest floor. Thus, *TF* variability will be a function of stand variables such as the canopy cover fraction, tree spacing, and the distance from a tree bole as well as rainfall intensity and wind speed, which combined determine the angle of

incidence at which P_g will strike the canopy (Carlyle-Moses and Price 2007). The *CV* of canopy cover in the stand was 48.3%, much smaller than the *CV* of individual wedge gauge catch for *TF* depths <3.5 mm (74.7%), suggesting that free throughfall variability is not strictly dependent on the variability of canopy cover fraction. The *CV* of canopy cover did, however, approach that of the *TF* ≥3.5 mm *CV* of 49.5%. Zhan et al. (2007) found, in a stand of Chinese pine (*Pinus tabulaeformis* Carr.) that the *CV* of *TF* remained quasi-constant at 17%–19% once P_g exceed 28 mm, while the *CV* of leaf area index (LAI) in their stand was 18%. The results in our study coupled with those of Zhan et al. (2007), suggest that the relationship between the variability associated with a canopy cover metric (canopy cover fraction, LAI) and that of *TF* needs to be further explored and that it might be possible to use the variability of these canopy metrics as a predictor of *TF* variability for those events that saturate a canopy.

Due to the large spatial variability of *TF* in our study stand an average of 94 wedge gauges and 40 trough gauges were required to obtain estimates of mean event *TF* ≥3.5 mm to within ± 10% at 95% confidence level, and many more gauges were needed for lesser *TF* depths. These findings suggest large expenditures, both in terms of time and monetary costs, are needed to obtain reasonable estimates of mean *TF* reaching the forest floor at the event scale, even during relatively large events. For relatively small events obtaining the aforementioned accuracy is not logistically feasible. For season-long *TF* estimates all three sampling methods required a feasible number of gauges, ranging from 32 roving wedge gauges to 56 stationary wedge gauges. However, if gauges were relocated after every P_g event and not after 15 mm of P_g fell, the estimated required number of gauges decreased substantially to 16 wedge gauges and 6 trough gauges.

Fewer trough gauges than wedge gauges are required to sample *TF* to the same degree of accuracy. On average 2.2 wedge gauges would have been required for every trough gauge to obtain the same degree of accuracy of the event scale mean *TF* estimate. However, it is important to note that the catch area of a trough gauge is 84 times greater than the catch area of a wedge gauge. This suggests that large spatial autocorrelation of *TF* input along a trough exists and that the total catch area of all the *TF* gauges used in a study should not be the only consideration in the design of a study but that the spacing of the gauges should also be considered. Keim et al. (2005) found that the lag associated with standardized variograms of *TF* in both young and old coniferous stands in the Pacific Northwest, USA, was 5 m, more than the two times the length of the troughs.

The roving gauge method is better suited than a fixed gauge approach for studying the quantitative importance of season-long *TF* due to the fact that the errors may be summed quadratically. Because of the increased efficiency of trough gauges and because of the statistical advantages associated with a roving gauge approach, using roving trough gauges would result in meeting any statistical objective with the least number of gauges. However, practical considerations should be considered. Trough gauges are more difficult to install in the field and are more expensive than wedge gauges. Furthermore, the number of roving wedge gauges required to sample season-long *TF* is manageable and thus we cannot rule out a roving wedge gauge approach for our study stand and for similar forests. If, however, due to logistical constraints, such as conducting studies in remote areas, a stationary gauge approach is used, our findings suggest the use of troughs over wedge-type gauges. We advocate that the stationary gauge approach not be completely abandoned in any study, but rather, where feasible, both roving and stationary gauges be used since stationary gauges allow for a detailed examination of the temporal variability associated with *TF* and I_c processes (Carlyle-Moses et al. 2004; Link et al. 2004; Keim et al. 2005; Wullaert et al. 2009). The *TF* temporal persistence results suggest that, at least on the floor of our study stand, there are relatively "wet" and "dry" *TF* points that persist throughout the season. The presence of these time-stable "wet" and "dry" areas may have important ecohydrological implications including soil moisture content and soil solution chemistry, root growth, forest floor vegetation composition, and nutrient cycling (Keim et al. 2005).

Acknowledgments
The authors would like to express their gratitude to R.D. Winkler (British Columbia Ministry of Forests and Range) for her assistance with compiling the site description section of this study.

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